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Applications of a simple underwater imaging model (SUIM) are presented, which help to identify limiting factors in conventional underwater imaging applications, such as diver visibility. The model includes the effects of scattering caused by particles as well as turbulent flow structure. The effect of path radiance is also discussed.

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LIMITING FACTORS IN UNDERWATER IMAGING APPLICATIONS

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1. Background

Underwater vision and diver visibility is one of the key research nd application topics dating back at least 150 years, when the Secchi disk was believed first put to use to estimate the turbidity of the ocean and lake waters. It is well known that the light attenuation effect of the water, both absorption but more importantly scattering, contributes to the degradation of image transmission. In general, scattering properties of the medium determine the outcome of the image transmission. In ocean and lake environments, such properties are conveniently described and measured by the scattering coefficient (b), which determines the probability that a photon will be scattered away from its original traveling direction per unit length by the medium molecules, constituents within the medium (i.e. particles), and turbulence [1]. The scattering parameter (b) is an integration of the volume scattering or phase function, β, which details such probabilities by the relative directions of incoming and out-going photons.

The point spread function (PSF) provides a more intuitive and direct measure of the imaging outcome. It gives the system response to a point source, and thus includes the effect of multiple scattering. It is the parameter of choice to study image transmission, optical sounding [2], and retrieval of optical properties [3]. Its Fourier transform, the Optical Transfer Function (OTF), is also widely used and at times considered interchangeable with the PSF. The magnitude of the OTF, the modulation transfer function (MTF), is sufficient for incoherent imaging purposes when phase information can be neglected.

The system response includes those from the imaging system itself, as well as the effects of the medium (water in our case). With known characteristics of the imaging system and correct modeling of the medium, theoretically it is possible to fully recover the original signal by reversion or deconvolution [4]. Mathematically PSF is equivalent to the beam spread function (BSF) [5] which can be modeled and measured more easily. It is apparent that with the knowledge of formed image and PSF, the original image can be restored, especially when the noise can be reduced with improved system setup or optimization [6]. Additionally, with the knowledge of the PSF, one can easily simulate the system outcome. This is valuable to system design, performance prediction, as well as underwater scene simulations, as it is based on the accuracy of the physical model of the system (medium included). Different models of PSF that are based on particulate scattering have been examined and compared [7]. The results show that 3 commonly used inherent optical properties (IOP) should be used in order to adequately describe the imaging transfer through the water. However, the variations of signal due to index of refraction changes in water are not accounted for.

2. SUIM: simple underwater imaging model

A simple underwater imaging model (SUIM) has been developed [8], to investigate the relative contribution of particle and turbulence scattering on underwater imaging and transmission. The key steps will be outlined briefly for the convenience of the readers.

Results developed in previous atmosphere research [9–12] are used with modifications to reflect in-water optical conditions. Optical turbulence in the ocean is primarily caused by index of refraction (IOR) variation as functions of temperature and salinity, compared to density variations found in the atmosphere. It has been shown that IOR fluctuations can be expressed as linear combinations of individual elements, both in terms of power spectrum and structure functions [13]. Following the Kolmogorov model [9], for a fully developed turbulent flow, under the inertial or convective regime, $2\pi/L_0 < \kappa < 2\pi/l_0$ (L_0 and l_0 denote outer and inner scale respectively; κ defines the wavenumber of eddies), the power spectral density of IOR of the ocean waters over the imaging range (r) can be expressed in the forms of [13, 14]

$$\Phi_n^K(\kappa, r) = K_3 \kappa^{-11/3}, \tag{1}$$

where $K_3 = B_1 \chi \varepsilon^{-1/3}$, and reflects the 3-dimensional optical turbulence strength. B_1 is a constant. ε is the kinetic energy dissipation rate. χ relates to the dissipation rate of temperature or salinity [14]. For simplicity

but without losing generality, one can assume only one factor dominates IOR fluctuations, although observations suggest both can contribute simultaneously [15]. It is apparent the above has the usual Kolmogorov form found in atmospheric studies [9–11] as $\Phi_n^K(\kappa,r)=0.033C_n^2(r)\kappa^{-11/3}$, where again the superscript K denotes Kolmogorov spectrum. C_n^2 is the structure constant of the IOR fluctuations in atmosphere, which describes the optical turbulence strength at distance r from the pupil plane (i.e. intensity of IOR fluctuations). We notice that K_3 is the equivalent of C_n^2, by a constant. The above scalar relationship implies that the turbulence in water can be considered statistically isotropic, homogenous, and wide-sense stationary (WSS) such that spatial autocorrelation function only depends on relative positions. We assume this is true at least in the imaging range.

It is commonly known that spatial coherence functions between optical fields of any two points can be used to describe the irradiance distribution of the source image or object [11, 16]. For a time-varying correlation function under WSS conditions, its ensemble average can be related to the spatial phase structure function, such that the optical transfer function (OTF) of a general incoherent object can be expressed following the approach by Fried [10, 12]. Consider that random phase changes of a wavefront can be described independently as a thin screen which exists only when turbulence exists, the resting or averaging OTF would be that of particles only. This assures linearity of system components, which allows the application of the cascading of optical transfer functions in the frequency domain [16]. From this, we can arrive at a simple underwater imaging equation accounts for particle [17], path radiance and turbulence scattering, in the form:

$$\begin{aligned} OTF(\psi,r)_{total} &= OTF(\psi,r)_{path}OTF(\psi,r)_{par}OTF(\psi,r)_{tur} = \\ &=\left(\frac{1}{1+D}\right)\exp\left[-cr+br\left(\frac{1-e^{-2\pi\theta_0\psi}}{2\pi\theta_0\psi}\right)\right]\exp\left(-S_n\psi^{5/3}r\right)= \\ &=\left(\frac{1}{1+D}\right)\exp\left\{-\left[c-b\left(\frac{1-e^{-2\pi\theta_0\psi}}{2\pi\theta_0\psi}\right)+S_n\psi^{5/3}\right]r\right\} \end{aligned} \tag{2}$$

where θ_0 relates to mean scattering. c is the beam attenuation coefficient. D is the normalized radiance received by the detector. The first term in the bracket reflects the effect of the path radiance [8]. It is worth pointing out that OTF_{par} can take many different forms, depending how the scattering phase structure is incorporated [7].

3. Application of SUIM

The simple underwater imaging model (SUIM), Eq. (2), accounts for particle, turbulence scattering as well as path radiance effects in the underwater environment. The primary aim of the model is to determine the relative contributions which are essential in assessing limits of conventional passive systems under different underwater conditions.

In an earlier study [18], the SUIM model was applied to diver visibility observations from several divers, and used to explain discrepancies between observations and the particle scattering only model. This model can also help to explain the extreme turbulence situation observed by Gilbert and Honey [15]. One of the targets used in their experiment is the standard USAF 1951 resolution chart, which is shown in Fig. 1. The chart uses black and white bar patterns of horizontal and vertical orientations at different spatial frequencies denoted by the number of line pairs per mm (Table 1). If one converts USAF line pairs to spatial frequencies, the first blurred line pairs, group –1, element 1, correspond to 650 cyc/rad at 1.3 m range. Applying Eq. (2) with $R_0 \sim 0.0005$, c ~ 0.3 m^{-1} which is the likely values in such waters ($\varepsilon = 10^{-5}$, $\chi = 10^{-11}$), one can see the total contrast easily decreases to <2 % within 1.3 m range (Fig. 2), which explains the complete disappearance of the group in the USAF chart observed at such short distance [15]. From Eq.(2) and Fig. 2, it becomes apparent why Mertens reported no frequency higher than 1 cyc/mrad observed in the

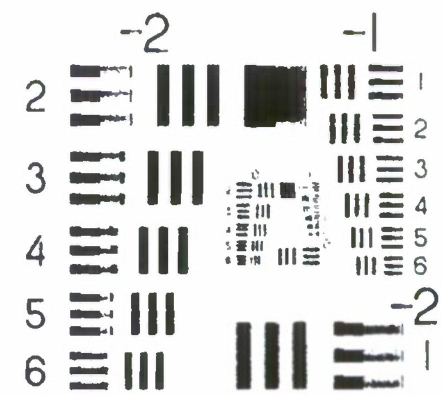

Fig. 1. Standard USAF 1951 chart. Each group consists of different elements, corresponding to different spatial frequencies denoted by number of line pairs per mm.

field, which puzzled Duntley [19], as at such high spatial frequency (~10^3 cyc/rad), the relative contrast decreases rather rapidly towards zero.

Table 1. USAF resolution chart, showing number of line pairs per mm of different groups and elements. Notice th spatial frequencies of first 4 elements of groups −2 to 1 at distance 1.3 m are shown in bracketed values

Number of line pairs per mm (USAF 1951)							
Element\Group#	−2	−1	0	1	2	3	4
1	0.250 (325)	0.500 (650)	1.00 (1300)	2.00 (2600)	4.00	8.00	16.00
2	0.280	0.561	1.12	2.24	4.49	8.98	17.95
3	0.315	0.630	1.26	2.52	5.04	10.10	20.16
4	0.353	0.707	1.41	2.83	5.66	11.30	22.62
5	0.397	0.793	1.59	3.17	6.35	12.70	25.39
6	0.445	0.891	1.78	3.56	7.13	14.30	28.50

The SUIM helps to assess the limitations of underwater imaging contributions by particles, turbulen and ambient illumination observed. It is important to observe the differences between particle and turbulen effects on underwater imaging, as shown by Fig. 2. While turbulence scattering can affect low frequen components, especially over longer range, its primary impact is on high frequency or details, which diffe from that of particles. It is also worth mentioning that the current SUIM reflects the optical properties of t medium under incoherent cases, although coherent cutoff frequency is often less [11], so it can be used a crude estimate even under partial coherent sources. Naturally it can be applied directly for conventio imaging and especially diver visibility assuming passive conditions. It is apparent that the SUIM does i include effects of backscattering, nor cases with saturation which only further degrades MTF, although first order this can be neglected since effects on all frequencies remain the same. Needless to say, it is i directly applicable to active systems such as gated and modulated, although modifications can be made reflect shorter integration time, to obtain system limitations similar to approach used in [12].

4. Summary

In this paper the relative contributions by both turbulence induced index of refraction variations as w as particle scattering on imaging outcome in natural environments are examined, using the recer developed SUIM model. Specifically, it is shown that by including turbulence effects which are based Kolmogorov power spectrum, we are able to explain the blurring of resolution patterns in very short dista in clean waters off the coast of Hawaii, observed by Gilbert and Honey. Further validation of the theory necessary, especially under different turbulence conditions and particulate concentration. The applicat range of the developed theory should also be tested, along with different turbulence models and subregime

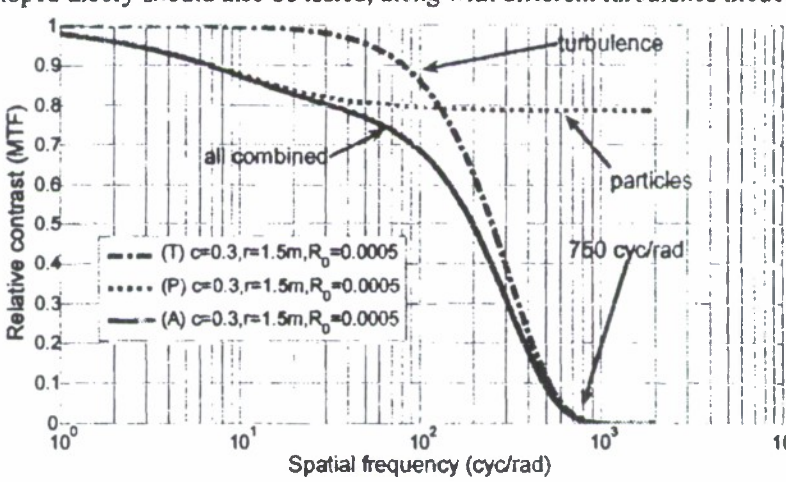

Fig. 2. Relative contributions by particle and turbulence scattering on MTF under a condition similar to that of Ha waters during Gilbert and Honey experiment (1972). Notice relative contrast drops to 2% at spatial frequenc 650 cyc/rad.

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